Arecibo timing observations of 17 pulsars along the Galactic plane

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ABSTRACT

We present phase-coherent timing solutions obtained for the first time for 17 pulsars discovered at Arecibo by Hulse & Taylor (1975ab) in a 430-MHz survey of the Galactic plane. This survey remains the most sensitive of the Galactic plane at 430 MHz and has comparable equivalent sensitivity to the 1400-MHz Parkes multibeam survey. Comparing both surveys we find that, as expected, the one at 430 MHz is limited in depth by interstellar dispersion and scattering effects; and that the detection rate of pulsars with high spin-down luminosity ($\dot{E} > 10^{34}\,\mathrm{erg\,s^{-1}}$) at the low frequency is a factor of 5 smaller than at high frequency. We also present scatter-broadening measurements for two pulsars and pulse nulling and mode-changing properties for two others.

Subject headings: pulsars: general

1. Introduction

The first systematic search for pulsars using the 305-m Arecibo radio telescope was carried out by Hulse & Taylor (hereafter HT) over 25 years ago (HT 1974, 1975a, b). The HT survey was conducted at 430 MHz and covered an area of about 140 square degrees in the region defined by $42^\circ \lesssim l \lesssim 60^\circ$ and $|b| \lesssim 4^\circ$. An integration time of 136.5 s resulted in a limiting flux density to long-period pulsars of about 1 mJy — roughly an order of magnitude more sensitive than any other pulsar survey at that time, and still the most sensitive low-frequency survey along the Galactic plane. A total of 40 pulsars were discovered, the most notable being the double neutron star binary system B1913+16 (HT 1975a) which has since been used as a magnificent laboratory for gravitational physics (Taylor & Weisberg 1982, 1989).

Pulse period, position and dispersion measure (DM) determinations for the 39 long-period pulsars were published shortly after the completion of the survey (HT 1975b). However, perhaps as a result of the interest in observations of B1913+16, timing observations have been carried out for only 22 sources (see e.g. Gullahorn & Rankin 1978). In this paper we report on new Arecibo timing observations of the remaining 17 pulsars which have resulted in accurate parameters for all of them. In § 2 we describe the observations and procedures used to obtain the timing solutions. The results are presented in § 3. We discuss scattering and single-pulse properties of the pulsars respectively in § 4.1 and § 4.2. Finally, in § 4.3, we briefly discuss the population properties of the sample and compare them with pulsars discovered in the 1374-MHz Parkes multibeam survey.

2. Observations and Analysis

The observations were carried out using primarily the 430-MHz line-feed receiver on the Arecibo telescope between 1999 May and 2000 November. During each session we observed all 17 pulsars, as well as the strong pulsar B1933+16 for control purposes. The incoming 430-MHz signals from both senses of circular polarization were amplified and down-converted to an intermediate frequency of 30 MHz. The Penn State Pulsar Machine (PSPM), a $2 \times 128 \times 60$-kHz filterbank spectrometer, was used to record the data in one of two modes. In "search mode", data are continuously sampled every $80\,\mu$s with 4-bit precision for each of the 128 frequency channels. Off-line processing proceeds by first producing a dedispersed time series in which successive channels are delayed in time by an amount corresponding to the nominal DM of each pulsar. The time series can then either be searched for periodic signals, or folded modulo a particular pulse period to produce an integrated pulse profile. In "timing mode", a custom-built chip is used to fold the incoming data for each frequency channel online. The resulting 128 profiles are then de-dispersed and summed to produce a single profile. In both operating modes, the PSPM is synchronized to start on a well-calibrated 10-s tick pulse so that all data can be used for timing purposes.

Since all of the existing ephemerides for these pulsars dated back to the original discovery papers published over 25 years ago, they could not be used to predict the topocentric period with sufficient accuracy to fold the data on-line. To obtain useful ephemerides, the first few sessions were used to make observations of each pulsar in search mode. From an analysis of these data, we obtained an up-to-date measurement of the period of each pulsar and verified that it was the fundamental period. Although good positional determinations were available for several pulsars as a result of previous observations (Weisberg et al. 1981; Vivekanand, Mohanty & Salter 1983), an improvement was necessary for several pulsars whose positions still had uncertainties on the order of the half-power width of the telescope beam (± 5 arcmin for the HT survey). Positions for these pulsars were improved by taking search-mode data for a number of offset telescope pointings about the nominal position and localizing the telescope pointing which gave the highest signal-to-noise ratio. The resulting period and position measurements were used to form ephemerides which were adopted in all subsequent observing sessions which used the PSPM directly in timing mode. Integration times ranged between 90 and 180 s, with weaker pulsars demanding longer integrations to obtain sufficient signal-to-noise ratio.

The analysis of the timing-mode profiles proceeded by forming a high signal-to-noise template profile for each pulsar. This was done in the first instance by shifting individual profiles so that the peak amplitude is at phase 0.5 before adding a number of them (typically 10 profiles) together. The time of arrival (TOA) of each profile was then calculated by convolution with the template and adding the resulting time offset to the time stamp recorded at the start of the observation. For further details of this procedure, see Taylor (1992). Based on this set of TOAs and the initial ephemeris used for the timing observations, we used the TEMPO[1] software package to fit a simple spin-down model consisting of four free parameters: pulse period, period derivative, right ascension and declination. The resulting ephemerides were then used to phase-align each observed profile to the midpoint before adding to produce a better template for each pulsar. This new template was then used to generate new TOAs which were in turn run through TEMPO to obtain a better ephemeris. This process significantly reduced the rms observed-minus-model TOA residuals, increasing the precision of the resultant parameter estimates.

Previously published DM measurements of the 17 pulsars often have uncertainties of the order $\pm 20\,\mathrm{cm}^{-3}\,\mathrm{pc}$. In order to make more precise DM measurements, in 2001 May we carried out multi-frequency timing observations at 1175 and 1475 MHz using the L-wide Gregorian receiver. Data for these observations were collected with the Wide-band Arecibo Pulsar Processor (WAPP) — a fast-dump digital correlator which samples a 100-MHz bandwidth (Dowd et al. 2000). Off-line dedispersion and folding of the WAPP data using the ephemerides

[1] http://pulsar.princeton.edu/tempo

derived above and standard data processing tools (Lorimer 2001) produced time-tagged integrated pulse profiles. Combining the resulting TOAs with the 430-MHz data, a fit for DM using TEMPO and holding all other parameters in the ephemeris constant yielded DM uncertainties of the order of a few $\mathrm{cm^{-3}\,pc}$, or less. We verified the validity of our analysis by fitting the 430-MHz TOAs separately with the 1175 and 1475-MHz data, which gave consistent results. We note also that our DM determination for J2027+2146 is in excellent agreement with the Hankins' (1987) measurement ($96.8 \pm 0.2\,\mathrm{cm^{-3}\,pc}$). As a final iteration, the new DM values were used to dedisperse the PSPM timing-mode data to produce definitive 430-MHz template profiles for all the pulsars. For several pulsars the improved DM resulted in a much sharper profile showing features that were previously unresolved due to dedispersion at the less precise DM value.

Due to the 4-bit quantization scheme used in the PSPM, the averaged pulse profiles obtained in timing mode range between 0 and 15 in each bin. The scaling factor to convert these profiles into flux density units is $1000 \times T/(D \times G)$, where T is the total system noise temperate (K), D is the DC offset of the profile (in PSPM counts), and G is the antenna gain ($\mathrm{K\,Jy^{-1}}$). With this choice of units, we obtain a profile in mJy. For Arecibo observations, both T and G are strong functions of the zenith angle, z, as both the illumination pattern and system noise temperature change from their optimum values at the zenith. To include these effects, we used the analytical expressions for $T(z)$ and $G(z)$ determined by Perillat (1999) from continuum source calibration observations. The adopted system temperature also includes the contribution from the sky background radiation obtained from the all-sky survey of Haslam et al. (1982).

Using this calibration technique, phase-averaged flux densities were obtained for each profile by simply calculating the area under each pulse and dividing this by the total number of bins in the profile. There was often a significant (few arcmin) offset between the positions used to point the telescope for the timing observations and the actual pulsar positions obtained following the timing analysis. As a result, our measured flux densities underestimate the true values slightly. To account for this, each measured flux density was multiplied by the correction factor $\exp(4\ln 2 \times \Delta^2/W^2)$ where Δ is the offset from the center of the assumed Gaussian telescope beam and W is the half-power beamwidth (10 arcmin for the 430-MHz system).

3. Results

The timing parameters, pulse widths and flux densities are presented in Table 1. Listed are pulsar name, right ascension and declination, pulse period P and its derivative $\dot{P}$, DM, equivalent pulse width w_e, pulse widths w_{50} and w_{10} measured respectively at 50 and 10% of the peak amplitude, and the mean 430-MHz phase-averaged flux density S_{430}. Separate values of w_{50} and w_{10} are tabulated for the three pulsars with double-pulse profiles. The equivalent width w_e is the width of a top-hat pulse having the same area and peak height as the profile. S_{430} is the mean of all the individual flux-density measurements. Using our data for PSR B1933+16, we find $S_{430} = 233 \pm 6\,\mathrm{mJy}$, in excellent agreement with the value of $242 \pm 22\,\mathrm{mJy}$ based on 408-MHz Jodrell Bank observations (Lorimer et al. 1995). Post-fit timing residuals and 430-MHz profiles[2] are shown in Figure 1.

Derived parameters listed in Table 2 are: distance d, calculated using the Taylor & Cordes (1993) Galactic electron density model; Galactic height $z = d \sin b$; 430-MHz luminosity $L_{430} \equiv S_{430} d^2$; spin-down age $\tau = P/(2\dot{P})$; spin-down energy loss rate $\dot{E} = 4\pi^2 I \dot{P}/P^3$ (where the moment of inertia I is taken to be $10^{45}\,\mathrm{g\,cm^2}$; Manchester & Taylor 1977); and dipole magnetic field strength $B = 3.2 \times 10^{19} (P\dot{P})^{1/2}$ Gauss.

[2]available online at the European Pulsar Network profile database: http://www.mpifr-bonn.mpg.de/div/pulsar/epn

Table 1. Observed parameters of 17 pulsars

PSR	R. A. (J2000)	Dec. (J2000)	P (s)	$\dot{P}$ (10^{-15})	DM ($\mathrm{cm}^{-3}\,\mathrm{pc}$)	w_e (ms)	w_{50} (ms)	w_{10} (ms)	S_{430} (mJy)
J1904+1011	19 04 02.49(2)	+10 11 34.6(5)	1.85656971650(7)	0.276(8)	135(2)	51	28;37	84;93	4.4(3)
J1907+1247	19 07 10.70(2)	+12 47 35.9(5)	0.82709737059(3)	1.948(4)	257(1)	19	20	33	0.8(1)
J1912+1036	19 12 46.33(1)	+10 36 41.6(3)	0.409349485862(6)	15.7620(8)	147.0(5)	16	15	31	1.6(1)
J1913+0936	19 13 52.70(2)	+09 36 41.8(3)	1.24196459936(3)	0.432(4)	157(2)	29	18	51	0.8(1)
J1921+2003	19 21 51.597(8)	+20 03 20.8(8)	0.76068138902(1)	0.050(1)	101(1)	13	8;11	15;27	2.3(1)
J1923+1706	19 23 07.85(1)	+17 06 09.4(2)	0.547209201831(8)	0.043(1)	142.5(6)	16	19	28	1.5(1)
J1926+1928	19 26 22.82(4)	+19 28 11.7(8)	1.34601218493(9)	1.43(1)	445(2)	47	54	88	0.8(1)
J1927+1852	19 27 10.422(8)	+18 52 08.5(2)	0.482766273821(7)	0.116(1)	254(1)	29	32	52	3.4(1)
J1927+1856	19 27 24.97(1)	+18 56 36.8(2)	0.298313497249(4)	2.2430(8)	99(1)	18	9	43	2.2(1)
J1929+1844	19 29 16.78(4)	+18 44 59.5(7)	1.22047000453(8)	2.36(1)	112(2)	25	25	49	1.7(2)
J1931+1536	19 31 55.71(1)	+15 36 57.5(3)	0.314355396469(6)	5.0148(9)	140(1)	12	11	27	1.2(1)
J1933+1304	19 33 22.529(4)	+13 04 49.97(8)	0.928323751417(5)	0.3182(7)	177.9(2)	16	7	37	2.0(1)
J1935+1745	19 35 29.97(1)	+17 45 12.2(2)	0.654408146583(1)	0.378(2)	214.6(4)	27	24	60	1.3(1)
J1942+1743	19 42 01.03(2)	+17 43 28.3(4)	0.69626221476(2)	0.101(3)	190(6)	42	46	92	2.8(1)
J1944+1755	19 44 31.80(4)	+17 55 42.4(7)	1.9968990135(1)	0.73(2)	175(2)	50	40;20	85;70	1.9(1)
J1945+1834	19 45 36.10(2)	+18 34 20.1(4)	1.06870769134(4)	0.242(5)	217.7(1)	28	28	49	1.2(1)
J2027+2146	20 27 16.690(3)	+21 46 04.43(5)	0.398173021652(2)	0.2028(2)	96.8(4)	9	6	21	0.7(1)

Note. — Epoch of period is 51600.0 (MJD) for all sources. Units of right ascension are hours, minutes, and seconds. Units of declination are degrees, arcminutes, and arcseconds. Figures in parentheses are $1\,\sigma$ uncertainties in the least-significant digits.

Table 2. Derived parameters of 17 pulsars

PSR	d (kpc)	z (kpc)	$\log L_{430}$ ($\mathrm{mJy\,kpc}^2$)	$\log\tau$ (yr)	$\log\dot{E}$ ($\mathrm{erg\,s}^{-1}$)	$\log B$ (G)
J1904+1011	4.0	0.13	1.9	8.03	30.23	11.86
J1907+1247	7.2	0.30	1.6	6.83	32.13	12.11
J1912+1036	4.2	0.01	1.5	5.61	33.96	12.41
J1913+0936	4.2	−0.04	1.1	7.66	30.95	11.87
J1921+2003	5.2	0.24	1.8	8.38	30.66	11.30
J1923+1706	6.4	0.11	1.8	8.30	31.02	11.19
J1926+1928	30	0.74	2.9	7.17	31.36	12.15
J1927+1852	10	0.17	2.6	7.82	31.61	11.38
J1927+1856	4.8	0.08	1.7	6.32	33.52	11.92
J1929+1844	5.3	0.04	1.7	6.91	31.71	12.23
J1931+1536	6.4	−0.18	1.7	6.00	33.80	12.10
J1933+1304	8.1	−0.44	2.1	7.66	31.20	11.74
J1935+1745	9.6	−0.22	2.1	7.44	31.73	11.70
J1942+1743	9.8	−0.46	2.4	8.04	31.07	11.43
J1944+1755	9.5	−0.51	2.2	7.64	30.56	12.09
J1945+1834	13	−0.67	2.3	7.84	30.89	11.71
J2027+2146	10	−1.68	1.8	7.49	32.10	11.46

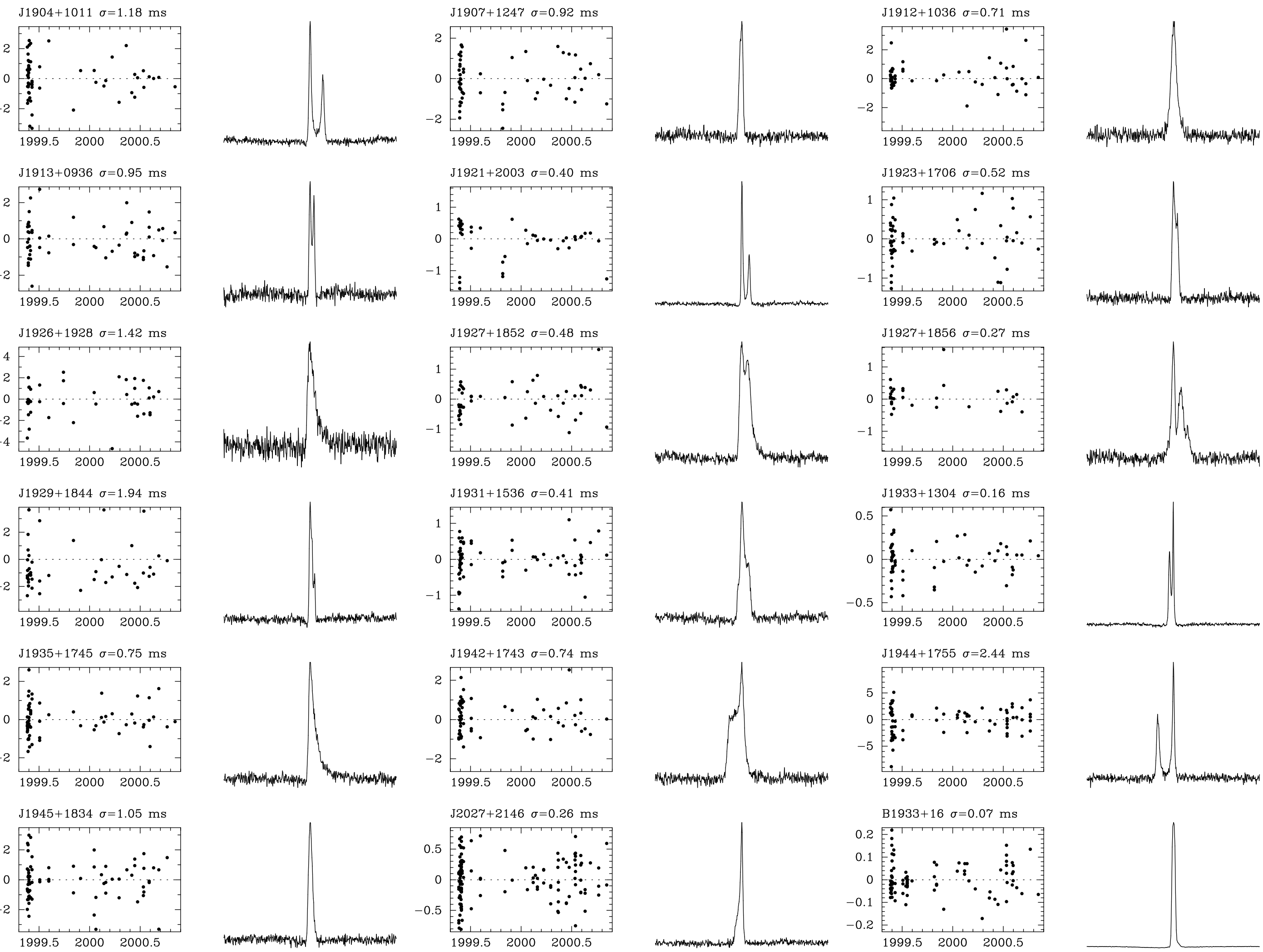

Fig. 1.— Post-fit timing residuals (in ms, with rms value given by σ) vs. date, and integrated pulse profiles from 430-MHz PSPM observations of 18 pulsars (including the calibrator PSR B1933+16). Profile time resolution is 2 milliperiods in all cases.

4. Discussion

4.1. Scatter Broadening of Pulse Profiles

The profiles for PSRs J1926+1928 and J1935+1745 (Figure 1) show clear examples of "scattering tails", the excess delay caused by multi-path scattering from irregularities in the electron density of the interstellar medium (Scheuer 1968). Different path lengths between scattered and unscattered rays result in a range of arrival times which broadens intrinsically sharp pulses in an exponential fashion. Fitting the observed profiles to a one-sided exponential function with a time constant τ_s using the procedure described by Löhmer et al. (2001), we find τ_s values of 47 ± 6 ms and 24 ± 1 ms for PSRs J1926+1928 and J1935+1745, respectively, at 430 MHz.

In general, the amount of scattering increases as the number of scattering electrons along the line of sight increases. From published measurements, Cordes (2001) finds the following empirical relationship:

$$\log \tau_s = -3.59 + 0.129 \log \mathrm{DM} + 1.02 (\log \mathrm{DM})^2 - 4.4 \log \nu,$$

where the units are μs, cm^{-3} pc and GHz for τ_s, DM and observing frequency ν, respectively. Note the use of the Kolmogorov power-law dependence $\tau_s \propto \nu^{-4.4}$ (see e.g. Rickett 1977) for frequency scaling in this expression. As noted by Cordes (2001) there is considerable variance about this best-fit expression for individual pulsars. This can be seen for PSRs J1926+1928 and J1935+1745 where the predicted values (329 and 7 ms respectively) differ significantly from our measurements. These differences reflect the variation in the clumpiness of the interstellar medium along different lines of sight, as well as the deviation from the theoretical power-law dependence on observing frequency (Löhmer et al. 2001).

Two other pulsars in Figure 1, J1907+1247 and J1927+1852, have predicted 430-MHz τ_s values of order 20 ms. Clearly no significant scattering tail is evident in the profile for J1907+1247. The profile for J1927+1852 appears to be possibly affected by scattering. However, the truncated exponential fitting procedure used above does not result in a good fit to this profile. A profile component analysis, using the procedure described by Kramer (1994), shows that the profile is best described by a simple three-component Gaussian model rather than any exponentially decaying components.

4.2. Single-Pulse Properties

After obtaining the timing solutions we dedispersed and folded the original search-mode PSPM data to examine the individual pulse properties. It was notable that the two longest period pulsars in the sample, PSRs J1944+1755 and J1904+1011 ($P \sim 2$ s), showed clear evidence for pulse-nulling: the abrupt switch-off of emission for many pulse periods (Backer 1970a). A sequence of 340 consecutive single pulses from J1944+1755 is shown in Figure 2. From a visual inspection of these data, we estimate that the nulling fraction is at least 60%. This is comparable with nulling observed in other long-period pulsars (Ritchings 1976). As can be seen in Figure 2, the pulsar often spends 1–2 min in a null. As a result, this pulsar would not have been discovered had it been in this state during the original observation of this position in the HT survey. The number of pulsars that have been missed by surveys with short integration times may be large. A detailed analysis of the nulling characteristics of pulsars found in the Parkes multibeam survey (Manchester et al. 2001), where much longer 35-min integration times are used, will be useful to quantify the population of nulling pulsars.

The nulling fraction for PSR J1904+1011 is harder to estimate since the signal-to-noise ratios of the individual pulses were lower. From the timing-mode profiles it is clear that there is more than one stable state of this profile. Approximately 90% of all timing-mode profiles collected were similar to the one shown in Figure 1, where the leading component is about twice the height of the second one. In the remaining 10% of the profiles, the second component was either of equal magnitude to, or stronger than, the first one. It seems likely that this pulsar exhibits mode changing (Backer 1970b; Lyne 1971).

The search-mode data we have collected are not ideal for detailed study of the single-pulse behavior. Integration times were sufficient for collection of only a few hundred pulses and the original telescope pointings were often offset significantly from the true positions obtained from the timing analysis. However, they do suggest that a dedicated program of single-pulse observations with the new ephemerides presented here would be a worthwhile addition to our existing knowledge of the nulling and mode-changing phenomena in general (Rankin 1986).

4.3. Population Properties

For many years, the HT survey, with a limiting 430-MHz flux density of ~ 1 mJy, provided the deepest sample of pulsars along the northern Galactic plane. The on-going Parkes multibeam (hereafter PM) survey, with a limiting flux density of 0.15 mJy at a center frequency of 1374 MHz, is now providing a much larger

sample of pulsars along much of the Galactic plane ($260° < l < 50°$ and $|b| < 5°$; Manchester et al. 2001). For a given pulsar spectral index α, the effective 430-MHz sensitivity of the PM survey is $0.15 \times (430/1374)^{\alpha}$ mJy. For the mean pulsar spectral index value of -1.6 (Lorimer et al. 1995) the nominal sensitivity limits of the HT and PM surveys are similar. Given this close match in sensitivities, it is interesting to compare the properties of the pulsars found in the two surveys.

HT (1975a, b) suggested that their search appeared to have detected a limit to the spatial extent of pulsars in the search region ($42° \lesssim l \lesssim 60°$ and $|b| \lesssim 4°$). This idea was based on the fact that only 2 out of the 49 pulsars detected in the HT survey had DM $> 260\,\mathrm{cm}^{-3}$ pc. The median DM value in the sample is only $165\,\mathrm{cm}^{-3}$ pc. For the 24 pulsars published so far from the PM survey[3] which are visible from Arecibo we see a much broader distribution in DM with a median of $347\,\mathrm{cm}^{-3}$ pc and a maximum value of almost $800\,\mathrm{cm}^{-3}$ pc. Rather than being a real effect, the DM cutoff seen in the HT sample reflects the selection effect against detecting highly scattered pulsars with large DMs in low-frequency surveys (see e.g. Johnston 1994).

In the period–period derivative diagram presented in Figure 3 we compare the spin properties of the HT pulsars with the currently available sample of 409 pulsars from the PM survey. Also shown on this diagram is the locus of points for which $\dot{E} = 10^{34}\,\mathrm{erg\,s^{-1}}$. The most striking difference between the two samples is the lack of high $\dot{E}$ objects found in the HT survey. Only 4% of the HT pulsars have $\dot{E} > 10^{34}\,\mathrm{erg\,s^{-1}}$ compared to 25% of PM pulsars found in the Arecibo declination range and 18% for the PM survey as a whole. Since high $\dot{E}$ pulsars are predominantly young, we can reasonably expect them to be found close to their birth sites on the Galactic plane. This effect is clearly seen in the sample of pulsars from the PM survey where almost 60% of the sample of objects with $\dot{E} > 10^{34}\,\mathrm{erg\,s^{-1}}$ are found at latitudes in the range $|b| < 0.5°$. Only 30% of the PM pulsars with $\dot{E} < 10^{34}\,\mathrm{erg\,s^{-1}}$ lie in the latitude range $|b| < 0.5°$. At these low Galactic latitudes the high sky background temperature on the plane, as well as pulse dispersion and scattering, significantly reduce the sensitivity of low-frequency pulsar surveys. These selection effects seem to be the most likely reason for the dearth of high-$\dot{E}$ pulsars in the HT sample.

The success of the PM survey in finding new pulsars in the Arecibo declination range implies that many further discoveries could be made by a large-scale Arecibo search using a 1400-MHz multibeam system. Development of such a system is currently underway and it is expected that it will be available sometime in 2003 (P. Goldsmith & J. Cordes, private communication). For integration times of about 300 s per pointing and bandwidths of about 200 MHz, a survey with the Arecibo multibeam system should be able to improve upon the sensitivity achieved by the PM survey by a factor of about 5. Although the pulsars observed in this study were the weakest subset of the HT sample (with 430-MHz luminosities ranging between 10 and 1000 mJy kpc^2; see Table 2), it is well known that the pulsar luminosity function extends down to 1 mJy kpc^2 at 430 MHz and probably much fainter (Lyne et al. 1998). Thus, in addition to finding many pulsars in general, a future Arecibo multibeam survey would be an excellent probe of the low end of the luminosity function for young pulsars.

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[3]http://www.atnf.csiro.au/research/pulsar/pmsurv/pmpsrs.db

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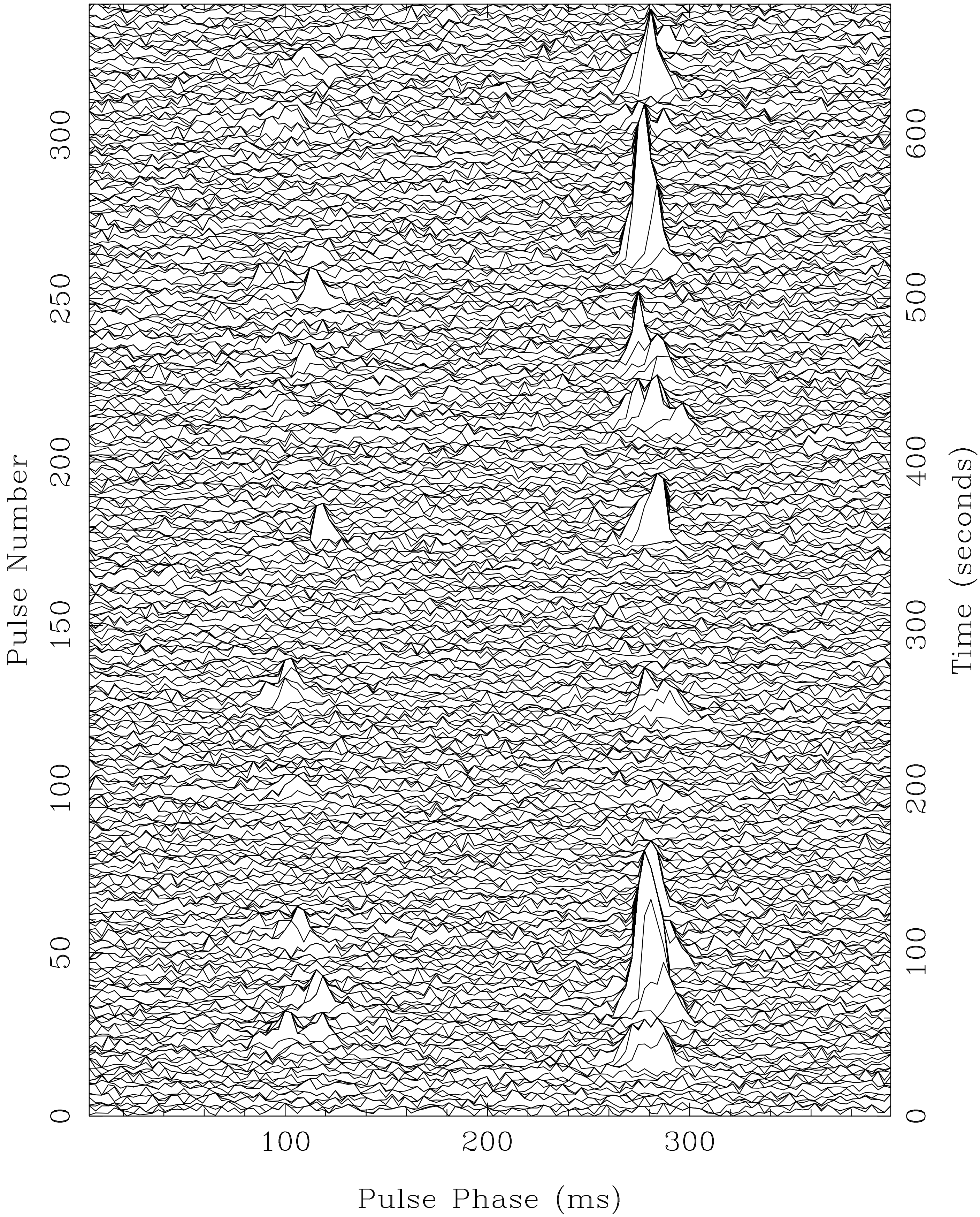

Fig. 2.— A sequence of 340 consecutive single pulses from the 2-s pulsar J1944+1745. For clarity, only the central 400 ms of pulse phase of each pulse is shown.

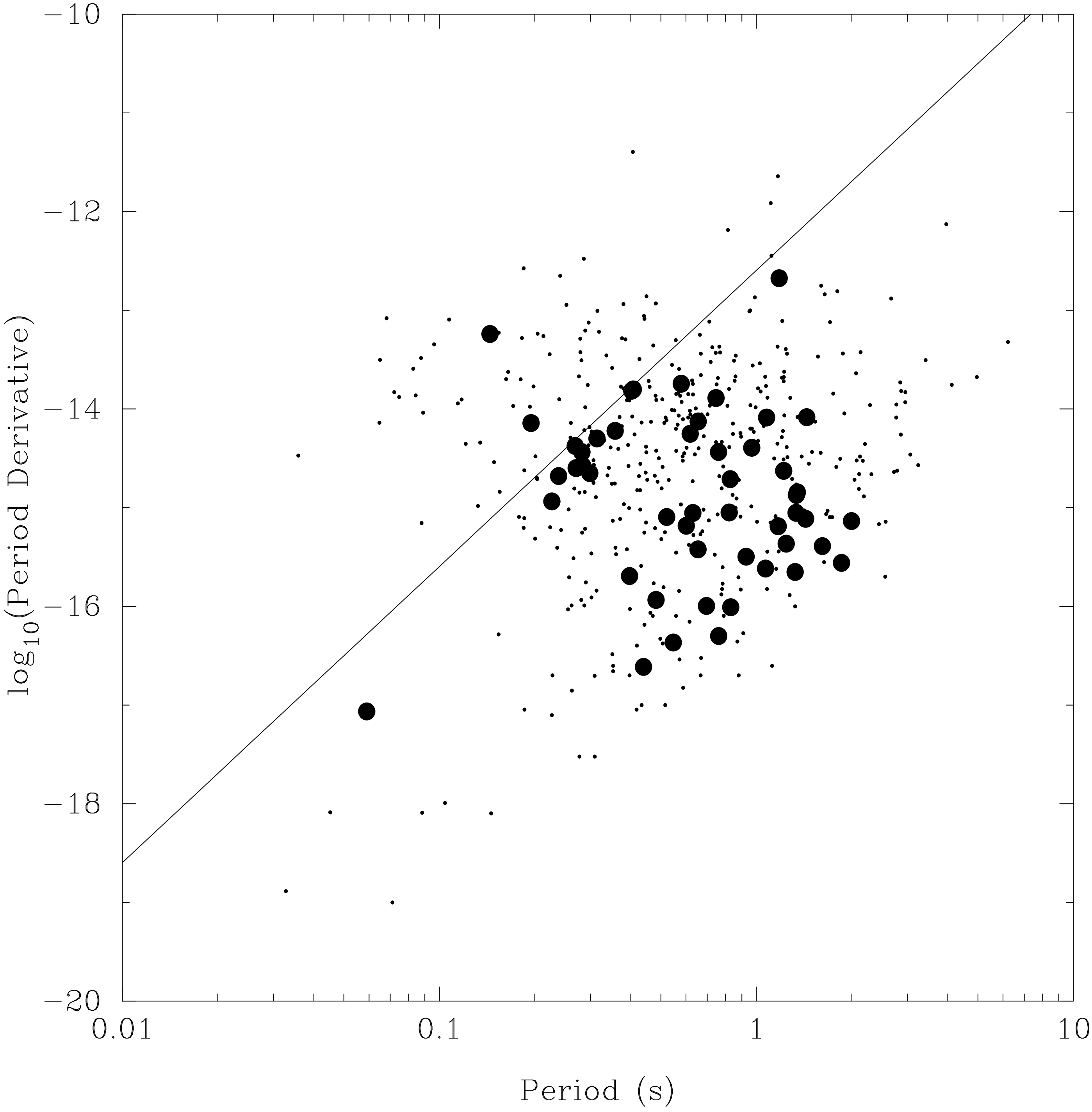

Fig. 3.— The P–$\dot{P}$ diagram. Large points represent all pulsars detected by the HT survey. Small points show the current sample of 409 pulsars from the PM survey. Pulsars to the left of the sloping line have $\dot{E} > 10^{34}\,\mathrm{erg\,s^{-1}}$. The fraction of such objects found in the PM survey is five times higher than for the HT survey.